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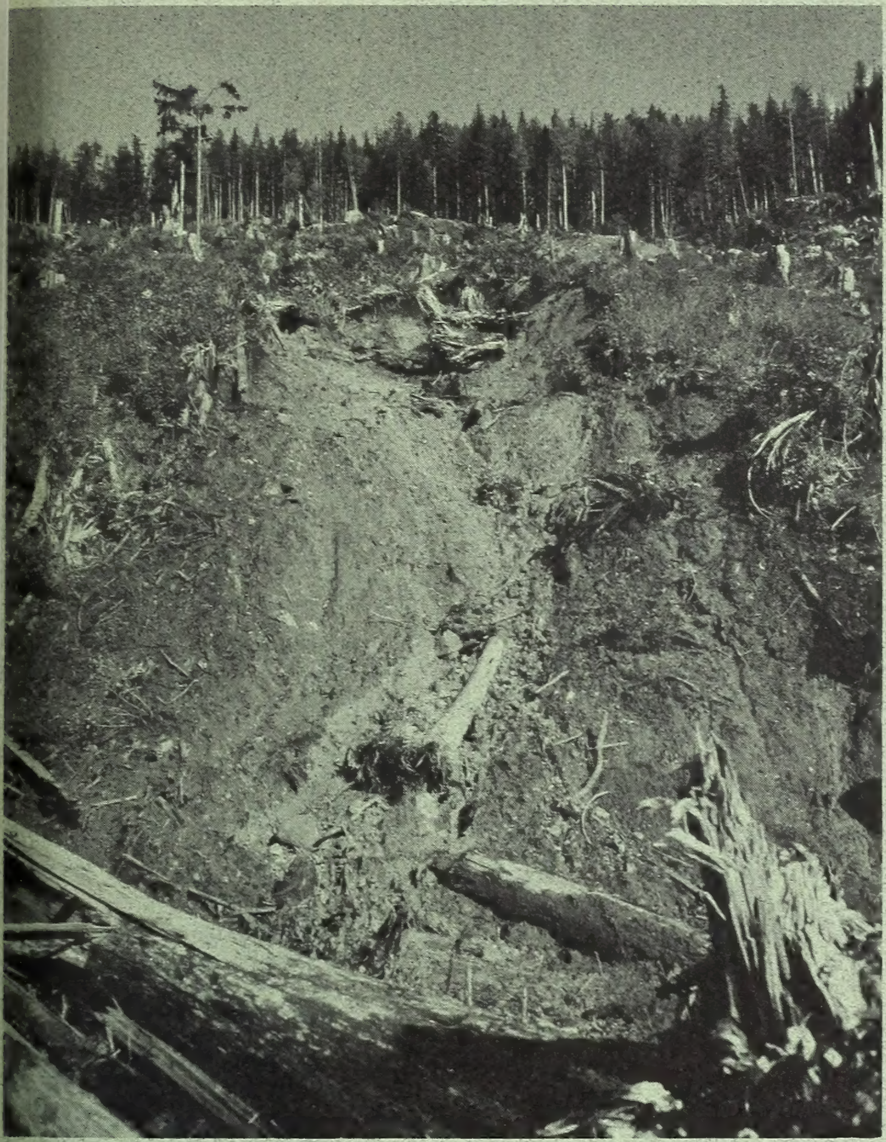

Mechanics of Debris Avalanching in Shallow Till Soils of Southeast Alaska

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CONTENTS

INTRODUCTION

Excessive slope gradient and pore-water stress in glacial till soils of the Karta series are primary factors in debris avalanche and flow occurrence in recently logged areas of southeast Alaska. Initial field investigations have indicated that during months of low rainfall, lateral movement of seepage water in these soils is limited to a zone 2 to 6 inches thick, directly above an impermeable, unweathered till surface. Seepage occurs along interconnected soil voids and partings produced by downslope growth of rootlets above this surface (Bishop and Stevens 1964, Swanston 1967a).[1]

During high rainfall periods, the soil becomes saturated, and the seepage zone thickens with substantial increases in flow. The increasing volume of water, moving laterally through the soil as saturated flow, causes a rise in the piezometric surface, with two important consequences: (1) increasing shear stress along potential sliding surfaces caused by rising seepage pressures and increasing unit weight of the soil materials, and (2) decreasing shear resistance resulting from increased pore-water pressure in the soil.

Historically, increased pore-water pressure has been shown to be a primary factor in the sliding mechanism of aggregate slopes. During periods of heavy rain, the quantity of water in the soil naturally increases. On saturation, excess water builds up, causing a rise in the piezometric level or "free" water level in the soil. The net effect is an increase in water pressure in the soil voids. Terzaghi (1950) has compared the effect of this increased pressure to the action of a hydraulic jack. The hydrostatic pressure of the water carries part or all of the weight of the overlying soil, in effect causing it to be jacked up or to "float," greatly reducing its "shearing resistance."[2]

Soil stability analyses, based on theoretical soil mechanics and modified by engineering experience and practice, have become standard procedures for engineering works involving steep natural, and constructed slopes with a potential slide hazard. Detailed descriptions of theory and practical application are presented in a number of texts, among them Terzaghi (1950, 1963), Terzaghi and Peck (1960), Hough (1957), Wu (1966), Taylor (1965), and Eckel (1958).

Direct application of theoretical soil mechanics principles to the evaluation of the effects of various physical parameters operative on natural slope soils is difficult because of the large number of variables involved. A number

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[1] Names and dates in parentheses refer to literature cited, p. 16.

[2] Shearing resistance is the resistance to a stress causing or tending to cause two adjacent parts of a solid to slide past one another parallel to a plane or contact.

of assumptions based on idealized conditions at time of failure and certain mathematical simplifications are required which limit the reliability of quantitative results. Such an analysis, however, does provide a useful means of estimating the forces known or believed to be acting on the slopes where sliding has occurred and of characterizing slopes according to their slide susceptibility.

This paper (a) reports on the applicability of standard soil mechanics techniques to an evaluation of the factors affecting debris avalanching in the steep, shallow, permeable till soils of southeast Alaska and (b) quantifies the relationships between these factors which, up to now, have only been suggested on the basis of field observations.

STUDY AREA

Maybeso Creek valley on Prince of Wales Island was chosen as the principal area of research. It was the location of the first large-scale clearcut in southeast Alaska, and an extensive road system had been developed allowing easy access to recent debris avalanching. Weather records had also been maintained for 10 years before these studies, with major debris avalanches noted. Finally, the valley is the center of the type area for the Karta soil series (Gass et al. 1967).

Three slide areas (fig. 1) in the valley were chosen for detailed study on the basis of accessibility and similarity of occurrence. Each of these developed during a heavy rainfall period in October 1961 and occurred in the soil zone of a continuous till sheet covering an oversteepened ($>30°$) south-facing slope. Timber was harvested during the summer seasons of 1955-58 by the high-lead method.

Figure 1.—The north slope of Maybeso Creek valley showing the location of the three slides analyzed.

METHODS

A stability analysis requires that the shear characteristics--effective cohesion, effective angle of internal friction, and unit weight--of the soils involved in sliding be obtained. It also requires that the effectiveness of pore-water stresses in the soil be evaluated and an approximate surface of failure determined.

Fundamental shear characteristics were obtained from undrained triaxial shear tests of five undisturbed soil samples[3] taken from the B horizon of the Karta soil at the head of the three recent debris avalanches studied. Estimates of bulk densities, moisture content, and particle size distribution were obtained from analyses of 19 additional randomly selected disturbed soil samples taken from the same areas.

Measurements of soil creep in the zone of sliding were made using strain gage probes modeled after those of Williams (1957).

The approximate surface of failure was determined in the field by assuming the base plane of the slide to be the surface of the unweathered till. The thickness of material above the slide plane and the gradient of the sliding surface were then measured. The toe of the initial zone of failure was taken as the first sharp break in slope within the slide scar and below the upper scarp. For convenience, the sliding surface was approximated by a "critical circle," tangent to the base plane and marked at its upper and lower limits by the upper slide scarp and the first break in slope not caused by bedrock. The critical circle had to satisfy the requirement that the ratio between the moment of forces tending to resist sliding (shear strength) and the moment of forces tending to cause sliding (shear stress) were at a minimum. This ratio is the factor of safety (F). At failure, F has a theoretical value of 1.

To determine the extent of pore-water pressure and evaluate its effect on mass movement in the till soils, piezometers were placed at selected sites within the three slide areas. These devices measure piezometric head or the height of rise of the free water above a reference surface. Pore-water pressure is directly related to piezometric head by the equation

$$\mu = h_p \gamma_w \tag{1}$$

where μ is pore-water pressure, h_p is piezometric head, and γ_w is the unit weight of water.

The piezometer, based on an original design by Casagrande (1949), is a porous carborundum tube, 6 to 12 inches long and 1-1/2 inches in outside

[3] When structural effects are to be observed in engineering tests, soil specimens are cut from natural formations and hand trimmed to usable size, reducing sample disturbance to an absolute minimum. This is an "undisturbed sample."

Figure 2.—Piezometer being lowered into auger hole near slide 3.

diameter, connected to 1/2-inch outside diameter polyethylene tubing (fig. 2). Three-inch holes were drilled with a bucket auger to a point approximately one-half inch below the unweathered till surface intersecting the zone of water movement. If water flowed freely into the hole, it was prepared for piezometer placement. Before placement, the depth of the hole to the unweathered till surface and the length of the piezometer system were measured.

Ten piezometers were installed during the latter part of August in 1964 and 1965 for measurements during the autumn rainy season. The sites were on open slopes within and outside linear depressions near the zone of initial failure of the three study areas. The slope angle measured at each location was between 34° and 40° (∿ 70- to 85-percent grade). Piezometer locations are shown in figure 3.

RESULTS

SOIL CHARACTERISTICS

The Karta soil is a well-drained shallow podzol with a gravelly, silt-loam texture (Gass et al. 1967). Mechanical analyses of 19 disturbed samples reveal it to be well graded, with a corresponding particle size distribution high in silt and sand with less than 10 percent being clay size particles.

Examination of the size fractions under a binocular microscope indicates the majority of particles to be angular to subangular in shape, composed of fragments of graywacke and argillite mixed with individual grains of quartz, feldspar, and ferromagnesian minerals.

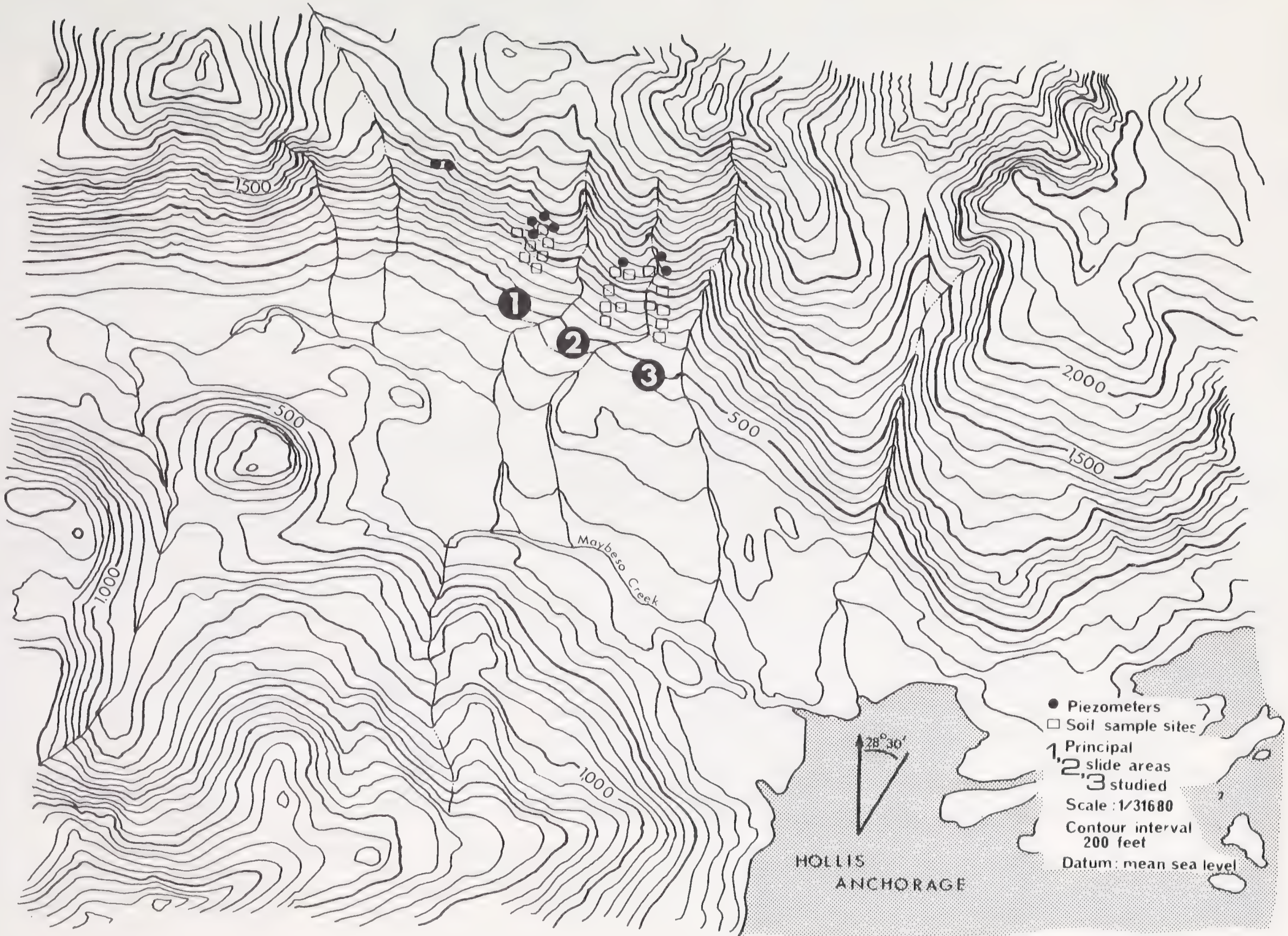

Figure 3.—Topographic map of a portion of Maybeso Creek valley showing locations of landslide study areas and sample and instrument sites.

Tests for Atterberg limits[4] made on five representative samples were inconclusive. In general, values were too low for interpretative purposes and are not reported here. Lack of well-defined Atterberg limits for the samples tested suggests that the effective internal cohesive forces in the slide-prone soil are minimal.

Triaxial shear tests on the five undisturbed samples[5] indicate an effective cohesion ($\bar{C}$) of 0 and an angle of internal friction of 37°. An effective cohesion of 0 supports the findings of the Atterberg tests.

Soil creep measurements[6] indicated moderate and recordable amounts of movement in the organic A horizon and upper part of the weathered B horizon with rate of creep estimated as one-fourth inch per year at the surface. The surficial soil apparently moves as a flow mass with no well defined shear zones. No significant deep-seated soil creep was indicated, ruling out a consideration of progressive failure of the slope at this time.

Surface loading of the soil due to weight of trees in the zone of initial sliding was considered negligible. Field observations and excavation of stumps in the study areas indicated that most of the weight of individual stumps was carried by lateral roots that penetrated the soil profile and lay on the compact, unweathered till surface (Bishop and Stevens 1964, Patric and Swanston 1968). These "lateral" roots were, in turn, anchored by small-diameter sinker roots that penetrated the upper 6 to 12 inches of the compact till surface. The decay of these roots following clearcutting or mortality may be an important factor in reducing resistance to sliding and will be taken into account in the analysis. It appears that any cohesion exhibited by these soils must result primarily from such factors as organic colloids, capillary tension, or anchoring effect of roots.

An effective 37° angle of internal friction serves as a good indication of the natural instability of these slopes. This angle is well above the theoretical maximum angle of stability (angle of repose)[7] for soil of the Karta type. The angle of repose can thus be used as a reference angle marking the maximum slope at which a soil of the Karta type will stand when unaffected by forces other than gravity and friction.

Unit weight values of the 19 random disturbed samples at field capacity (approximately 65-percent moisture content) averaged 111 pounds per cubic foot. Unit weights (air dry) were somewhat lower, averaging 103 pounds per cubic foot at a moisture content of 37 percent. These averaged values lie

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[4] Atterberg limits describe the states of consistency or firmness of a fine-grained soil.

[5] Triaxial shear tests performed by Michigan State University, Civil Engineering Laboratory.

[6] D. J. Barr and D. N. Swanston. Measurement of creep in a shallow, slide-prone till soil. (In preparation for publication.)

[7] The angle of repose is the angle between the horizontal and the slope of a heap of sand produced by pouring dust-dry sand from a small height. Experimentation and engineering field experience indicate that the angles of internal friction for loose sands, silts, and silty sands are similar, varying around an angle of repose of 34° (Terzaghi and Peck 1960, p. 66).

within the range of expected unit weight values for the Karta soil[8] and will be used in this paper as an index of the unit weight of the slide-prone soils.

PORE-WATER PRESSURE MEASUREMENTS

Pore-water pressure measurements during the fall rainy season (September through November) were begun in 1964 and continued in 1965 (Swanston 1967a, b). Direct correlation of both the 1964 and 1965 field data with rainfall variations recorded in the valley indicate a close relationship between these parameters.

A more detailed regression analysis of the 1965 field data (Swanston 1967b) revealed a curvilinear relationship between rainfall, pore-water pressure, and slope position, allowing us to make direct approximations of prevailing piezometric levels at the time and point of initiation of known landslide activity (fig. 4). Within the three selected study areas, rainfall conditions and slope position at the time of initial slope failure indicate conditions of total soil saturation to be in effect. Thus, for purposes of slope analysis, we can assume that the slide-prone soils were subjected to maximum pore-water pressures at the time of initial slope failure.

[8] Freeman Stephens, Soil Scientist, U. S. Forest Service Region 10, personal communication.

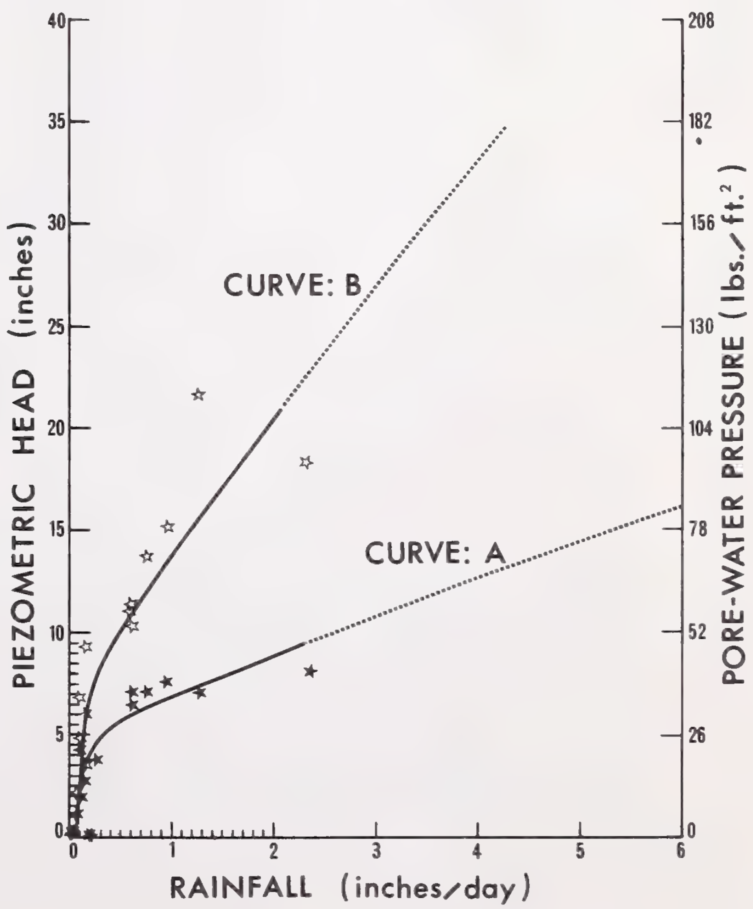

Figure 4.—Curvilinear relationship of average piezometric head vs. rainfall for two slide-prone slope locations. Curve A represents piezometric head on the open slopes; Curve B represents piezometric head within linear drainage depressions (after Swanston 1967b).

STABILITY ANALYSES

Final stability analyses were based on theoretical soil mechanics in homogeneous materials, with results modified by engineering experience. The analyses were made using "the method of slices," as described by Wu (1966) and Hough (1957). This method allowed shear strength-stress relationships and the factor of safety to be calculated with reasonable accuracy. It is especially useful when pore pressure effects are being considered. With this method, the soil mass as defined by field measurements is diagramed and divided into a number of segments (fig. 5). The forces acting on each segment are then evaluated assuming equilibrium conditions. Equilibrium occurs with balance between opposing forces.

If the shear stress is not sufficient to produce failure, then the ratio of shear strength to shear stress represents the factor of safety mentioned earlier. The factor of safety is given by the equation:

$$F = \frac{\Sigma[\bar{C}\Delta L + (\Delta W_n + Q_n - \mu\Delta L) \cos\alpha \tan\bar{\phi}]}{\Sigma(\Delta W_n + Q_n) \sin\alpha} \qquad (2)$$

where ΔW_n represents the weight of the soil, Q_n represents surface loading, μ is pore-water pressure, ΔL is slope width of each section, α is slope angle, $\bar{\phi}$ is effective angle of internal friction and $\bar{C}$ is effective cohesion of the soil.

Since surface loading of the slide-prone soils is assumed negligible, the term Q_n can be removed from equation 3 and the factor of safety becomes:

$$F = \frac{\Sigma[\bar{C}\Delta L + (\Delta W_n - \mu\Delta L) \cos\alpha \tan\bar{\phi}]}{\Sigma\Delta W_n \sin\alpha} . \qquad (3)$$

The greatest pore pressure at failure in each of the three slide zones analyzed was taken as the pore-water pressure developed when the soil profile became completely saturated. Dimensions needed for solving equation 3 were scaled from longitudinal sections of the initial failure zone (fig. 5). The weight of each segment was determined by multiplying the segment area (from the scaled diagram) by the soil unit weight. The slope angle (α) was also measured directly from the diagram.

Calculation of F for the individual slide areas, using the previously determined shear characteristics of $\bar{\phi} = 37°$ and $\bar{C} = 0$, resulted in values for the F factor which are less than 1 (0.395, 0.396, and 0.449 for slides 1, 2, and 3).

At failure, F is assumed to be 1. The discrepancy existing here was removed by assuming the existence of a cohesive force in the soil that did not show up directly in laboratory tests. The existence of such a force (expressed as $\bar{C}_a$) is well illustrated in the field by many extremely steep but stable natural slopes.

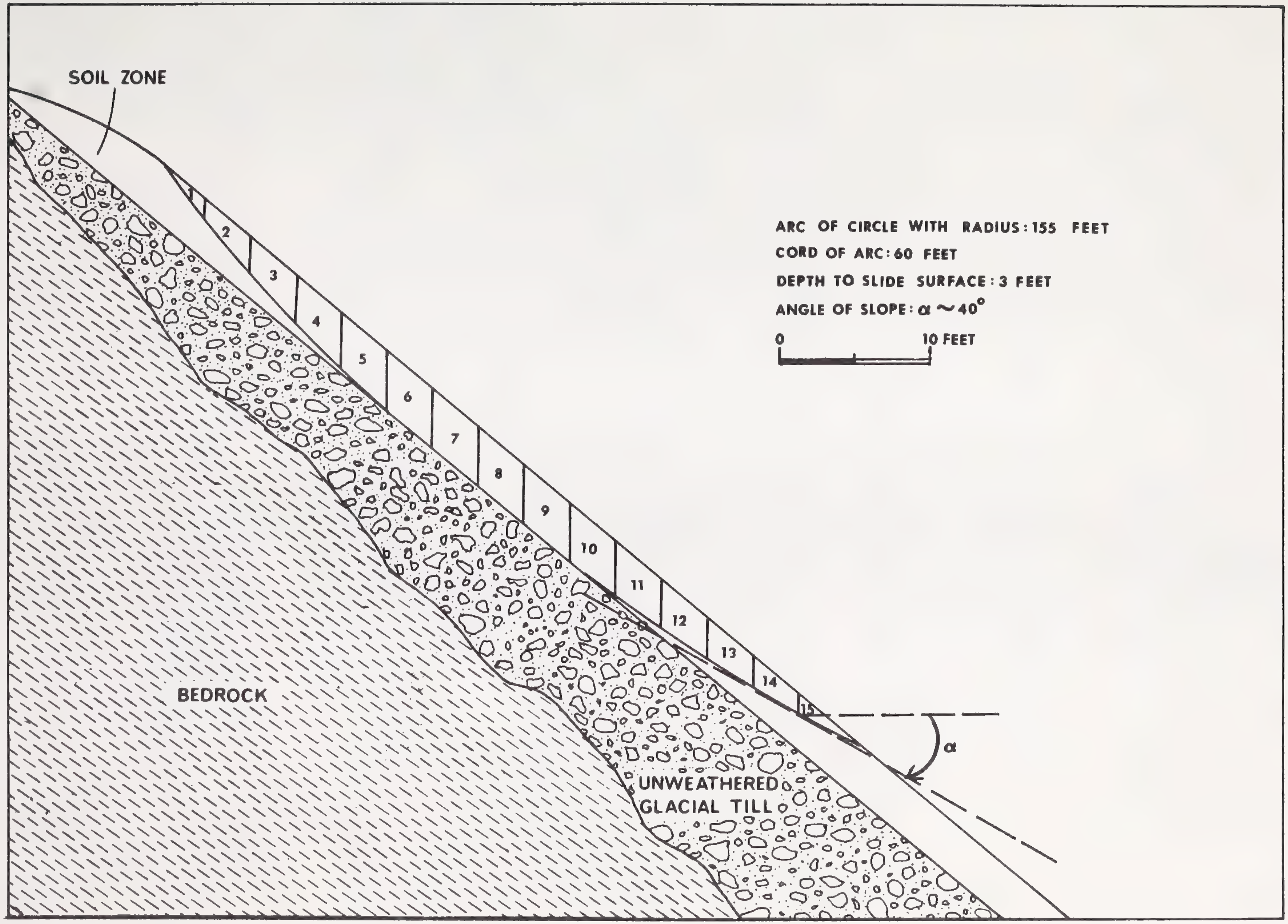

Figure 5.—Circular arc constructed from the measured dimensions of the initial zone of failure in each of the three slides studied.

This force may result from the interaction of several different factors. Capillary tension causes a limited amount of "apparent cohesion," prior to complete saturation of the soil profile. Some cohesion probably also results from the high organic colloid content (reported by Stephens 1967) of the slide-prone soils. A potentially large stabilizing force is produced by root penetration through the soil and into the compact till. Regardless of its primary cause, such a force may be estimated by setting the value of F at 1 and calculating an approximate value of $\bar{C}_a$ for each slide mass at failure and under the influence of pore-water pressure. Thus

$$F = 1 = \frac{\Sigma[\bar{C}_a \ \Delta L + (\Delta W_n - \mu\Delta L) \cos \alpha \tan \bar{\phi}]}{\Sigma(\Delta W_n) \sin \alpha}$$

and

$$\bar{C}_a = \frac{[1] \ [\Sigma\Delta W_n \sin \alpha] - [\Sigma(\Delta W_n - \mu\Delta L) \cos \alpha \tan \bar{\phi}]}{\Sigma\Delta L} . \qquad (4)$$

Calculations of "apparent cohesion" from equation 4 yield values for $\bar{C}_a$ of 89.15 pounds per square foot for slide 1, 83.9 pounds per square foot for slide 2, and 69.0 pounds per square foot for slide 3.

Using these $\bar{C}_a$ values, an F value at maximum soil strength for each of the study sites was also obtained. The F values of the slope with soils at their field capacity and air-dry states in the absence of active pore-water pressure were calculated and compared to determine the natural stability of the slopes and the effectiveness of pore-water pressure as a stability reducer. The calculated factors of safety for the soil at field capacity are 1.49, 1.57, and 1.61 for slides 1, 2, and 3. Those of soil in the air-dry state are 1.55, 1.62, and 1.66. The difference in F value for a soil at wet and dry unit weights is small. These values indicate more than adequate stability under natural soil and slope conditions and in the absence of water pressures, since values as low as 1.1 are frequently considered adequate for highway and railroad slopes (Hough 1957). *At complete saturation, and thus maximum pore-water pressure, these values are reduced to a factor of safety approaching 1 and sliding becomes imminent.*

A simple check can be made on the results of the method of slices by analyzing the forces acting on a block of unit thickness having the soil and slope characteristics on a slope of infinite length (fig. 6). The results are certainly less exact but provide an index of the correct magnitude of forces involved.

In Maybeso valley:

$\gamma_{sat.} = 111$ lbs./ft.^{3}

$\gamma_w = 62.4$ lbs./ft.^{3}

$\bar{\phi} = 37°$

$h = 3$ ft.

$\alpha = 37°$

$\Delta W = \gamma_{sat.}\ h$

$\tau = \Delta W \sin \alpha = \gamma_{sat.}\ h \sin \alpha$

$\sigma = \Delta W \cos \alpha - \gamma_{sat.}\ h \cos \alpha$

$\bar{\sigma} = (\gamma_{sat.}\ h - \gamma_w h) \cos \alpha$

$S = \bar{C} + \bar{\sigma} \tan \bar{\phi}$

Factor of safety $(F) = \dfrac{\bar{C} + \bar{\sigma} \tan \bar{\phi}}{\tau}$ (at failure F = 1)

thus,

$$1 = \frac{\bar{C} + (\gamma_{sat.}\ h - \gamma_w h) \cos \alpha \tan \bar{\phi}}{\gamma_{sat.}\ h \sin \alpha}$$

$$\bar{C} = \gamma_{sat.}\ h \sin \alpha - (\gamma_{sat.}\ h - \gamma_w h) \cos \alpha \tan \bar{\phi}$$

$$= (111)\ (3)\ (0.602) - [(111)(3) - (62.4)(3)][0.799][0.754]$$

$$= (200.46) - (333.00 - 187.2)\ (0.799)\ (0.544) - (145.8)\ (0.602)$$

$\bar{C}_a = 112.631$ lbs./ft.^{2}

using this value of $\bar{C}_a$, in the absence of pore-water pressures

$$F = \frac{112.00 + 200.46}{200.00} = 1.56.$$

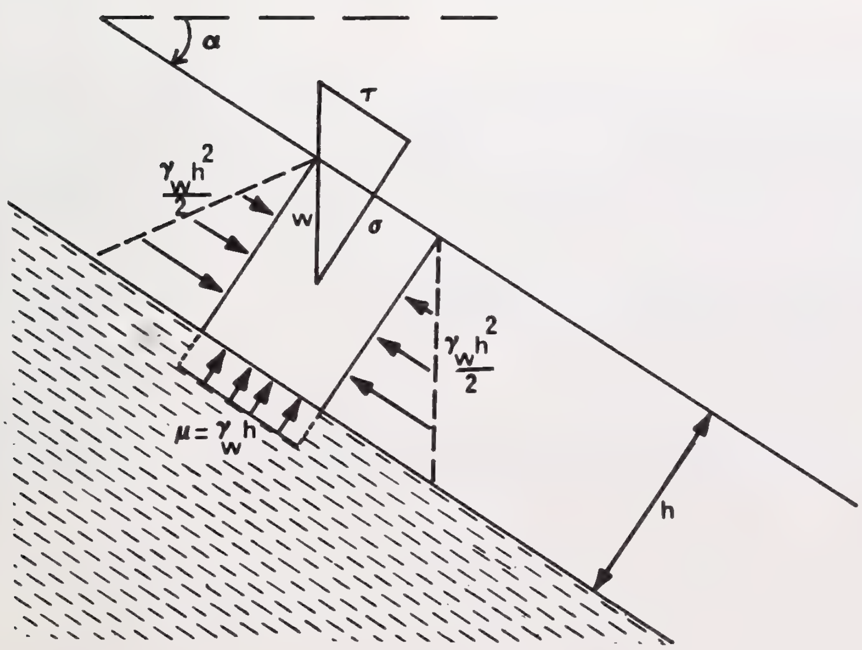

Figure 6.—Forces acting on a soil block having the soil and slope characteristics of unit thickness on a slope of infinite length. These forces consist of the weight of the soil ($W = h\gamma_{sat.}$), the normal and shear stresses (σ) and (τ), pore-water pressure (μ), and the lateral pressures on the block $\frac{\gamma_w h^2}{2}$ which cancel each other. α is the angle of slope, γ_w, unit weight of water, and $\gamma_{sat.}$, unit weight of soil.

DISCUSSION

This study verifies a number of previous assumptions concerning the effects of slope angle and various soil conditions on stability of steep slope till soils in southeast Alaska. In addition, many of these relationships have been quantified into values usable by the land manager for determining stability potential for specific management areas with this soil type.

High pore-water pressure stands out as the most effective triggering force for debris avalanches with maximum effect at complete saturation of the soil profile in the area of initial sliding. Field measurements in Maybeso valley indicate that such a completely saturated condition requires a rainfall intensity in excess of 6 inches in 24 hours, a condition known to have occurred during the 1961 period of slide activity in the valley and elsewhere in southeast Alaska (Bishop and Stevens 1964, Swanston 1967a). Similar intensities have been reported in the valley relating to sliding activity in 1959.

Swanston (1969) has shown that debris avalanching in southeast Alaska, regardless of soil type, is concentrated in areas of recurring high precipitation. They occur especially frequently in areas characterized by the same storm precipitation rate indicated in Maybeso valley. Thus, till soil areas with rainfall intensities frequently at or above the rate of 6 inches in 24 hours or which lie within areas of recurring high precipitation can be expected to have a high debris avalanche potential.

It is also clear that an apparent cohesion for the slide-prone soils does exist and is due to external factors not reflected directly in the physical properties of the soil. In the areas studied, this value varies from 69 to 89 pounds per square foot. Such an apparent cohesion is most likely to have resulted from the anchoring effect of roots growing through the slide-prone weathered till and into the underlying compacted and unweathered till. Bishop and Stevens (1964) suggested this possibility. They also noted an apparent 3-year lag in slide acceleration after logging and suggested that this may be the time necessary for root deterioration to reduce soil shear strength to a low enough value for sliding to occur. More recent investigations of root deterioration following logging in southeast Alaska[9] indicate a definite 3- to 5-year lag in root strength reduction and appearance of decay.

The upper limit of stability lies at or near 34° (the angle of repose of the soil). With decreasing slope, shear strength and the factor of safety increases. This can be seen by once again considering equation 5 for the factor of safety. If we assume a unit volume of soil not influenced by pore-water pressure and remove summation signs, equation 4 reduces to

$$F = \frac{\bar{C}\Delta L + W_n \cos\alpha \tan\phi}{W_n \sin\alpha} . \qquad (6)$$

[9] D. N. Swanston, and W. J. Walkotten. The effectiveness of rooting as a factor of shear strength in the Karta soil. Study No. FS-PNW-1604:26; report on file at the Pacific Northwest Forest and Range Exp. Sta., Northern Forest., Juneau.

Under the assumed conditions, $\bar{C}$ is a constant and ΔL or thickness of the soil mass is unity. W_n is also unity, and ϕ is constant. With decreasing slope, $\sin\,\alpha$ decreases faster than $\cos\,\alpha$. The F value correspondingly increases as the slope gets smaller. *This points up the strong relationship between slope angle and slide susceptibility.*

Strahler (1956) has developed a method of slope analysis that expresses this relationship particularly well. By determining the sines of the slope angles for a large number of points in an area, an isosinal map can be made by contouring the values. For cohesionless soils, the sine of the slope angle represents that part of the total gravitational force acting to produce downhill sliding or flowage of rock particles or fluids on the surface. A soil particle located at point "P" on the slope is affected by forces $F_g = mg.$, where m is mass in pounds and g is the acceleration of gravity in feet per second per second, F_s is shear stress (τ) in pounds per square foot. F_s and F_n are components of F_g. The elementary trigonometric relationship of the principal forces acting on a soil particle on a slope (Strahler 1956) is depicted in figure 7.

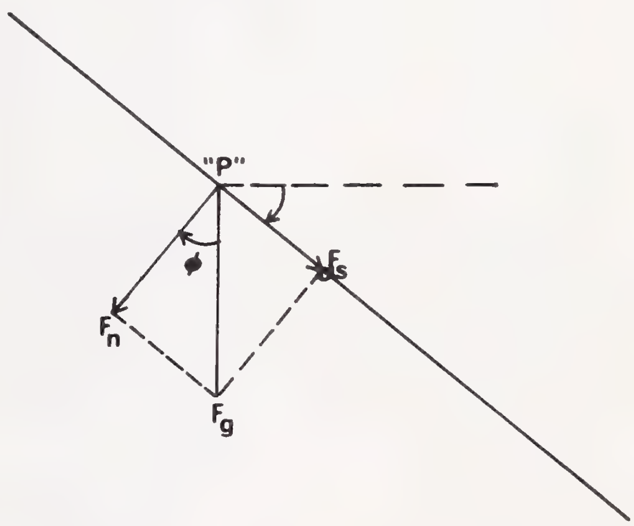

Figure 7.—Principal forces acting on a soil particle on a slope (after Strahler 1956). F_g represents the force of gravity acting on the particle, F_s is the shear stress, and F_n is the force normal to the surface. α is the angle of slope and ϕ is the angle of internal friction.

$$\sin\,\phi = \frac{F_s}{F_g}\,\frac{\tau}{F_g}, \text{ by geometry, } \alpha = \phi.$$

When a unit mass of soil surrounding point "P" on the slope is considered, the downslope force [shear stress (τ)] operating on that mass is given as $\tau = F_g \sin\,\alpha$, the equation for the shear stress in a cohesionless soil. Note that F_g in this case represents the column or weight of material.

Thus, the isosinal contour map tells the general location and distribution of shearing stresses produced by gravity on a cohesionless soil slope. Simply stated, for a cohesionless soil the factor of safety as defined by Terzaghi and Peck (1960) is:

$$F = \frac{\tan\,\phi}{\tan\,\alpha}, \tag{7}$$

As the slope angle approaches the internal friction angle, F approaches 1 and failure is imminent. The isosinal contour corresponding to the sine of the internal friction angle can then be used as the critical isosine around which sliding is most likely to occur.

A nonrigorous isosinal slope analysis, or more simply *slope angle analysis*, can supply useful results as to the effect of slope angle on soil stability and the most likely areas of future slide occurrence.

CONCLUSION

Studies in the Maybeso valley show that the majority of debris avalanches and flows develop on slopes greater than 34° and are especially frequent around a critical angle of 37°. On an isosinal contour map of Maybeso valley (fig. 8), this angle is represented by the critical contour 0.6, the sine of 37°. Above this critical contour, sliding is imminent with the destruction or disruption of any cohesive forces acting to hold the soil in place. Below the critical contour is a zone of decreasing instability. The zone of instability thus defined is located principally in the deeper stream notches and in a narrow band near the 1,200-foot contour. The narrow band in the vicinity of maximum slide activity corresponds to the steep face of a till shoulder marking the upper limit of younger till.

By construction of an isosine map, or more simply mapping of slope angles, areas of general slope instability within a watershed can be located and the feasibility of applying preventive or control measures determined. If the area of instability is a bedrock cliff, no additional consideration need be given. If the area lies within some of the best timber stands, serious thought should be given to harvesting techniques and road construction in the critical area.

Figure 8.—Isosinal contour map of the Maybeso Experimental Forest, Prince of Wales Island, Alaska. The sine of the angle of slope, or "isosine," expresses slope in terms of that part of the total gravitational force which tends to produce downhill sliding or flow of rock particles or fluids on the surface. The same lines can also be used to express slope angle or percent grade directly. Initial slope angles were obtained from a topographic map at a scale of 1:31,680 by counting the number of contour lines intersected by a perpendicular line, bisecting a slope point and corresponding to a ground distance of 200 feet (≈ one-half inch at map scale). The heavy black contour denotes the critical isosine or slope angle above which sliding is imminent under the best of conditions.

LITERATURE CITED

Bishop, Daniel M., and Stevens, Mervin E.
1964. Landslides on logged areas in southeast Alaska. Northern Forest Exp. Sta. USDA Forest Serv. Res. Pap. NOR-1, 18 pp., illus.

Casagrande, A.
1949. A nonmetallic piezometer for measuring pore pressures in clay. Appendix of soil mechanics in design and construction of the Logan Airport. J. Boston Soc. Civil Eng. 36(2).

Eckel, E. B.
1958. Landslides and engineering practice. Nat. Res. Counc. Highway Res. Board Spec. Rep. 29, No. 21, 232 pp.

Gass, C. R., Billings, R. F., Stephens, F. R., and Stevens, M. E.
1967. Soil management report for the Hollis area. USDA Forest Serv., Tongass Nat. Forest, Alaska Reg., 118 pp., illus.

Hough, Benjamin K.
1957. Basic soils engineering. 513 pp. New York: The Ronald Press Co.

Patric, J. H., and Swanston, D. N.
1968. Hydrology of a slide-prone glacial till soil in southeast Alaska. J. Forest. 66: 62-66, illus.

Stephens, F. R.
1967. Southeast Alaskan podzols--orthods or andepts. Agron. Abstr. 59: 122.

Strahler, A. N.
1956. Quantitative slope analysis. Geol. Soc. Amer. Bull. 67(5): 571-596.

Swanston, Douglas N.
1967a. Geology and slope failure in the Maybeso Valley, Prince of Wales Island, Alaska. 206 pp., illus. (Ph. D. dissertation on file at Mich. State Univ.)

____
1967b. Soil water piezometry in a southeast Alaska landslide area. Pacific Northwest Forest & Range Exp. Sta. USDA Forest Serv. Res. Note PNW-68, 17 pp., illus.

____
1969. Mass wasting in coastal Alaska. Pacific Northwest Forest & Range Exp. Sta. USDA Forest Serv. Res. Pap. PNW-83, 15 pp., illus.

Taylor, D. W.
1948. Fundamentals of soil mechanics. 700 pp. New York: John Wiley & Sons, Inc.

Terzaghi, Karl.
1950. Mechanism of landslides. *In* Application of geology to engineering practice. Geol. Soc. Amer., Berkey vol., pp. 83-123.

____
1963. Theoretical soil mechanics. 510 pp. New York: John Wiley & Sons, Inc.

__________ and Peck, R. B.
1960. Soil mechanics in engineering practice. 566 pp. New York: John Wiley & Sons, Inc.

Williams, P. J.
1957. The direct recording of solifluction movements. Amer. J. Sci. 255: 705-715.

Wu, T. H.
1966. Soil mechanics. 431 pp. Boston: Allyn & Bacon.

Swanston, Douglas N.
1970. Mechanics of debris avalanching in shallow till soils of southeast Alaska. USDA Forest Serv. Res. Pap. PNW-103, 17 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

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The mission of the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is to provide the knowledge, technology, and alternatives for present and future protection, management, and use of forest, range, and related environments.

Within this overall mission, the Station conducts and stimulates research to facilitate and to accelerate progress toward the following goals:

1. Providing safe and efficient technology for inventory, protection, and use of resources.
2. Development and evaluation of alternative methods and levels of resource management.
3. Achievement of optimum sustained resource productivity consistent with maintaining a high quality forest environment.

The area of research encompasses Oregon, Washington, Alaska, and, in some cases, California, Hawaii, the Western States, and the Nation. Results of the research will be made available promptly. Project headquarters are at:

College, Alaska	Portland, Oregon
Juneau, Alaska	Roseburg, Oregon
Bend, Oregon	Olympia, Washington
Corvallis, Oregon	Seattle, Washington
La Grande, Oregon	Wenatchee, Washington

The FOREST SERVICE of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.